

Focused ion beam fabrication of photonic structures in silicon-on-insulator

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Focused ion beam is a direct-write technique to make sub-micrometer structures in various materials. A finely focused beam (spot size $<10\text{nm}$) of gallium ions is accelerated onto the target material, in this work silicon or silicon oxide, where it removes atoms. In this way we can make waveguides, gratings, facets, photonic crystals, and much more.

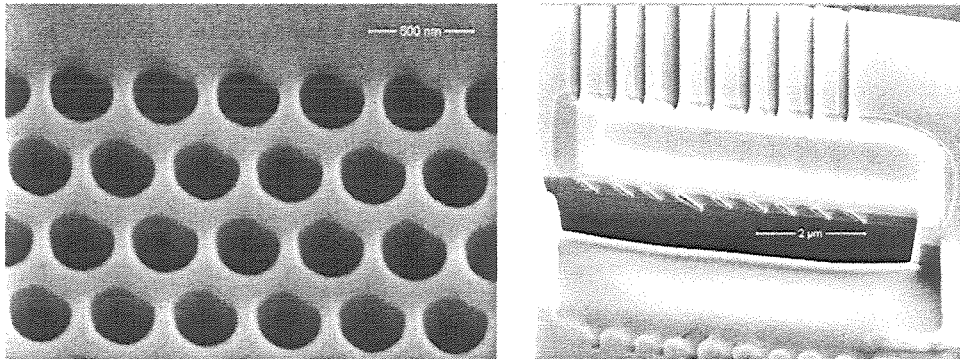


Figure 1: Left: photonic crystal holes;
Right: a slanted grating to couple light from chip to fiber.

One of the problems however, is that there is not only removal of silicon atoms, but also implantation of gallium atoms and displacement of silicon atoms in the crystal. These effects generate optical losses through various physical phenomena. A first phenomenon is amorphization: by implanting the silicon with a high dose of gallium atoms, the crystalline state is not stable and an amorphous phase appears with a depth of typically 60nm. This phase can have higher losses than the crystalline state.

A second phenomenon is optical losses by carrier absorption. Gallium acts as p-dopant in silicon and the free holes induce considerable optical loss.

The goal of my work is to understand these various phenomena and to explore techniques to reduce the optical losses. A first alternative is the use of an etch catalyst, like iodine. This gas eases the extraction of silicon atoms and reduces optical losses. Another possibility is to do annealing at temperatures up to 800 degrees, to restore the crystal damage and to let the gallium atoms diffuse out of the silicon, into the silicon oxide.

Focused ion beam for Photonics: A new versatile fabrication method

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Idea

Nanophotonics:

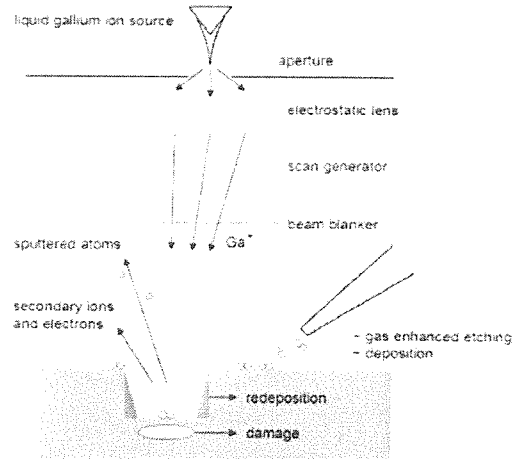
- Difficult to design (3D simulation)
- Nanometer fabrication precision required

Lithography

High cost and most expensive tools
do not reach 100nm resolution

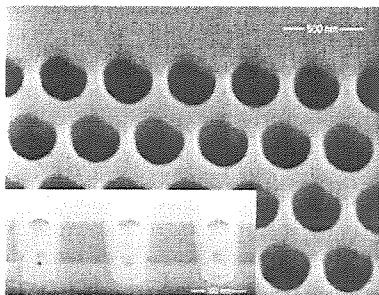
Focused ion beam:

- < 20nm resolution
- Fast and cheap prototyping
- 3D fabrication

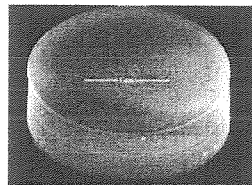


Ring resonator tuning

Slanted facet etching



Photonic Crystal prototyping



Micro disk laser
prototyping

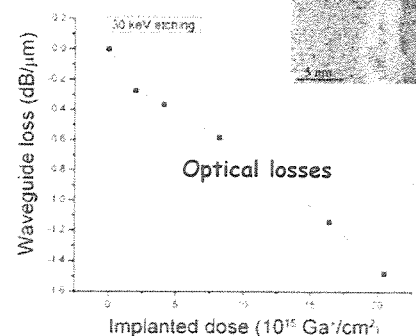
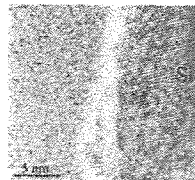


Slanted grating
fabrication

- Crystal damage
- Ion implantation
- Amorphization
- = Optical losses

Problem

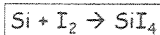
Silicon
amorphization



Optical losses

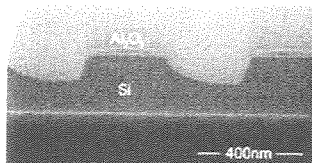
Solution

- Protective mask
- Etch enhancement gasses



Chemical reaction with iodine increases etch rate
and causes less ion implantation en crystal damage

Successful
fabrication of grating
couplers for light
coupling between
optical chip and fiber



Outlook

- Recrystallization of Si and out-diffusion of Ga ions by annealing at high temperatures (> 800°C)
- Application of similar processes to III-V semiconductors

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Applications of Photonic Integration

11 – 17 March 2007
Pontresina (CH)
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Poster Session 1

1. **Luc Augustin:** Integrated 2x2 polarization splitter/converter on InP/InGaAsP
2. **Yohan Barbarin:** High Power Electrically Pumped Modelocked VECSEL
3. **Aude-Reine Bellancourt:** First Demonstration of a Modelocked Integrated External-Cavity Surface Emitting Laser (MIXSEL)
4. **Robert Bellini:** Soft-matter photonics on anisotropically etched silicon
5. **Krister Bergeneek:** Enhanced Light Extraction from AlGaInP LEDs with a Shallow 2D Photonic Crystal
6. **Audrey Berrier:** Impact of the feature size on the optical properties of photonic crystal devices
7. **Pietro Binetti:** Membrane couplers and photodetectors for optical interconnections on CMOS ICs
8. **Jonathan Bradley:** Al₂O₃ and Y₂O₃ Waveguides as Building Blocks for Active Integrated Photonic Devices
9. **Mike Bülters:** A Vertical Electroabsorption Transceiver Consisting of Multiple Heterostructures
10. **Marek Chacinski:** Evaluation of low cost mounting techniques for high speed multi-electrode lasers
11. **Shahina Mumthaz Chakkalakkal Abdulla:** Tuning of Photonic Band Gap Crystals by NOEMS Actuators
12. **Wout De Cort:** A silicon laser with gain in doped liquid crystal
13. **Peter Debackere:** Surface Plasmon Interferometer: Fabrication and Measurement
14. **Boudewijn Docter:** Deep etched DBR mirrors for compact integrated lasers
15. **Jose David Domenech Gomez:** Analysis of non-uniform integrated optics Bragg gratings using GNU/GPL MEEP FDTD
16. **Rafal Dylewicz:** Inductively coupled plasma etching of GaN using SiCl₄/Cl₂/Ar for submicron-sized features fabrication
17. **Stephen Elsmere:** Fiber Amplification of VECSEL seed pulses
18. **Dimitri Geskus:** Fabrication of optical active devices in KYW:Yb
19. **Oliver Haderer:** Liquid Crystals for Photonics Applications
20. **Lina Huang:** Statistical study of optical trapping efficiency
21. **Koen Huybrechts:** All-Optical Flip-Flop Operation using an AR-coated Distributed Feedback Laser Diode
22. **Olena Ivanova:** Variational effective index mode solver
23. **Roman Kappeler:** Simulations on Contacting Schemes for Active Photonic Crystals (PhC)
24. **Peter Kaspar:** Electrical Contacts on Active Photonic Crystal Structures
25. **Edwin Klein:** Reconfigurable Optical Router based on vertically coupled thermally tunable Si₃N₄/SiO₂ microring resonators
26. **Abigaël Kok:** Modeling of efficient coupling structures for integration of pillar photonic crystal waveguides with ridge waveguides
27. **Christian Koos:** Ideal Contour Trajectories for Low-Loss Waveguide Bends
28. **Antonio La Porta:** Design of an integrated multiwavelength laser with RF optical modulator for burst-mode transmitters in packet-switching based metropolitan area networks
29. **Maria Latorre:** Bathymetry Analysis by Lidar Signal
30. **Tomas Lauerman:** Modeling of nonlinear propagation in a microring resonator
31. **Szymon Lis:** SiO₂ – TiO₂ Thin Film for Integrated Optics Fabricated by the Sol-Gel Technique
32. **Ping Ma:** Design, Fabrication and Characterization of Photonic Crystal Slab Waveguides for TM-Polarized Light
33. **Deran Maas:** First Demonstration of a Modelocked Integrated External-Cavity Surface Emitting Laser (MIXSEL)
34. **Antonio Malacarne:** An optical Flip-Flop Based on Erbium-Ytterbium Doped Fibre
35. **Fabien Mandorlo:** Integration of a CMOS compatible electrically pumped InP based micro laser
36. **Milan Marell:** Non-linear behavior in quantum-well polarization converters

Poster Session 2

37. **Ahmad Rifqi Md Zain:** Tapered Periodic Photonic Crystal (PhC) micro-cavity filters embedded in a ridge waveguides
38. **Gabor Mezosi:** Semiconductor Ring Laser Bistables
39. **Pascual Munoz:** Design of Multiwavelength Arrayed Waveguide Sagnac Interferometer-based Terahertz Optical Add Drop multiplexers
40. **Paolo Navaretti:** 1.3 μm all-GaInNAs modelocked VECSEL
41. **Patrick Nedel:** Fabrication of Photonic Quantum Information Devices based on InAs Quantum Dots and GaAs Photonic Crystals
42. **Guido Piaszenski:** 3D pattern definition via UV-Nanoimprint Lithography
43. **Roberto Proietti:** Unrepeated 16x10 Gb/s DPSK transmission over 140 km single-mode fiber by means of two commercial SOAs
44. **Antonio Quattieri:** Colloidal nanocrystals air bridge fabricated by direct lithography
45. **Adrian Quarterman:** Active stabilisation of VECSEL sources
46. **Roxana Ileana Rebigan:**
47. **Lars Rindorf:** Integrated photonic crystal fibers for biosensing and photonic components
48. **Gunther Roelkens:** A die-to-wafer bonding approach to photonics integration
49. **Richard Royce:** Lasing characteristics and physical properties of 1.3 μm emitting modulation doped quantum dot lasers.
50. **Benjamin Rudin:** First Demonstration of a Modelocked Integrated Absorber External-Cavity Surface Emitting Laser (MIXSEL)
51. **Jonathan Schrauwen:** Focused ion beam fabrication of photonic structures in silicon-on-insulator
52. **Ekber Selcuk:** Guided self-organized anisotropic strain engineering through step engineering on shallow-patterned substrates for complex quantum dot ordering
53. **Yaocheng Shi:** Carrier lifetimes in dry-etched InP-based photonic crystals
54. **Joanna Skiba-Szymanska:** Record high nuclear magnetic field in a 40 nm InP quantum dot
55. **Nut Sritirawisarn:** Surface morphology induced InAs quantum dash-dot shape transition on InGaAsP/InP (100)
56. **Tiziana Stomeo:** Integrated Photonic Crystal devices in InP-membrane for metropolitan optical networks
57. **Patric Strasser:** Photonic crystal etching process characterization: Losses, carrier lifetime and surface roughness
58. **Mikael Svalgaard:** High precision AFM characterization of planar photonic crystals
59. **Dominik Szymanski:** Ultrafast all optical switching using photonic crystals integrated into a Mach Zehnder interferometer
60. **George The:** Single-photon detectors for multiple-photon number resolution and other applications
61. **Ruth Thompson:** Ultra-Compact Integrated Interferometric Devices for Pulse Regeneration
62. **Mark Thompson:** Pulse Generation in Quantum Dot Laser Diodes
63. **Frederik Van Laere:** Polarization diversity and wavelength monitoring in BCB-bonded InP-membranes.
64. **Wouter Van Parys:** Transparent amplifying waveguide optical isolator
65. **Kristof Vandoorne:** A Photonic Implementation of Reservoir Computing
66. **Yongqiang Wei:** 10 Gb/s modulation of 1.3 μm GaInNAs lasers up to 110 $^{\circ}\text{C}$
67. **Christopher Wiesmann:** Altering the Radiation Pattern of Light Emitting Diodes by 2D Photonic Crystals
68. **Georg Winzer:** Low birefringence Mach-Zehnder-Delay Interferometer on Silicon-on-Insulator (SOI) substrates
69. **Ling XU:** A reflective transceiver at 1.55 μm for the access network
70. **Jing Yang:** Judd-Ofelt Analysis of Nd(TTA)₃Phen-doped 6-FDA/Epoxy Planar Waveguides
71. **Hua Zhang:** Fabrication, Electrical and Optical Characterisation of Terahertz Microdisk Quantum Cascade Lasers
72. **D Zhou:** Position and Number Control of InAs Quantum Dots Grown on Truncated InP Pyramids by SA MOVPE